Defense Technical Information Center Compilation Part Notice

This paper is a part of the following report:

- *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention. Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

- *To order the complete compilation report, use:* AD-A325 558

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

CONDITION MONITORING OF AIRCRAFT BY QUANTITATIVE FILTER DEBRIS ANALYSIS (QFDA)

L.G.I. Bennett and Sarah Swanson
Department of Chemistry and Chemical Engineering
Royal Military College of Canada - Collège militaire royal du Canada
Kingston, Ontario, Canada K7K 5L0

F.D. Koza and J.S. Poland
Department of Chemistry, Queen's University
Kingston, Ontario, Canada K7L 3N6

Abstract: Various condition monitoring techniques are used collectively to monitor the health of aircraft engines and transmissions, a concept known as Integrated Health Monitoring (IHM). A well-established quantitative technique is Aircraft Oil Analysis (AOA) in which spectroscopic techniques such as Rotating Disk Electrode Atomic Emission Spectroscopy (RDE-AES) is employed to analyse periodic oil samples for wear debris. Usually, no sample preparation is undertaken as the oil sample containing both dissolved and suspended metallic wear debris is analysed directly. AOA works well for oil-lubricated systems with relatively coarse filtration that allows circulation of the debris and its subsequent abrasive contact with moving components. To avoid this secondary wear, finer filtration is employed on new and older aircraft. Less wear debris, and thus information, is available in the oil. A technique that quantitatively analyses the wear debris caught on the filter has been developed and is termed Quantitative Filter Debris Analysis (QFDA).

Actual oil filters from Challenger ALF 502L-2C and Hornet F404 engines were obtained in sequence, when possible, prepared with the developed procedure and analysed with AOA instrumentation. With sufficient results, both normal and abnormal levels of wear rates have emerged, as has been recorded and used for AOA. Moreover, trending of the data for sequential samples has demonstrated the capability of QFDA for condition monitoring.

Key Words: ALF 502L-2C engines; condition monitoring; F404 engines; integrated health monitoring; quantitative filter debris analysis

INTRODUCTION: Integrated Health Monitoring (IHM) is the collection, analysis and application of many types of data related to the life usage and the mechanical and aerodynamic health of an aircraft's engine and drive train which will assist in its operation, maintenance, management, design, safety and logistics [1]. Condition Monitoring (CM) techniques are used to repair or replace components depending on their analysed condition rather than on a fixed schedule that the manufacturer recommends to prevent failure.

The overall concept of IHM uses CM techniques, such as wear debris analysis, to monitor the health of aircraft engines and related components. By monitoring the condition of aircraft engines, maintenance personnel may be able to predict engine failure before it occurs and reduce costly repairs.

The nature and quantity of wear debris (material, size, shape and concentration) are indications of the condition of various machine components which are in contact with the lubricant. The higher the concentration of metal particles and the larger the particles being generated, the more severe the wear [2]. The identity of a particular component as well as the specific wear processes can be determined by Filter Debris Analysis (FDA) and the level of wear (and thus engine health) can be determined by Quantitative Filter Debris Analysis (QFDA).

Currently, a tendency towards finer oil filtration (10 microns or less) in aircraft engines restricts the applicability of the present oil analysis methods in the Canadian Forces (CF) [3]. Although fine filtration removes the risk of secondary damage caused by wear debris, there is now insufficient debris remaining in the oil for valid analysis. However, the wear debris may be made available for analysis, both qualitative (FDA) and quantitative (QFDA), by cleaning the filter of debris and preparing it for an analytical technique.

SAMPLE PREPARATION: Known metal samples were used to develop and test the sample preparation procedure [4] and then actual oil filters were analysed. After the engine filters were received from the various CF Bases, they were cleaned ultrasonically with a solvent and the wear debris was then filtered. (At this step, the morphology of the wear particles may be inspected qualitatively by FDA). The filter patch was then dissolved by acid digestion. At this second step, the debris could be analysed quantitatively by Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). However, in order to determine if the Rotating Disk Electrode Atomic Emission Spectroscopy (RDE-AES) available for AOA could be employed, a third step was developed. To prepare the solid sample for quantitative analysis by RDE-AES, it must be converted into an oil-based form. All of the oil filters were cleaned of debris (step 1) and the debris was digested with acid (2), converted into an oil matrix (3), and then analysed by RDE-AES.

(1) Ultrasonic Cleaning: Engine oil filters from the Hornet and Challenger aircraft were cleaned by a combination of ultrasonic agitation and filter backwashing in Petrosol solvent with low pressure (3 psi) pulsating air. This cleaning technique [3] was developed to ensure that the metallic wear particles enmeshed in the engine filter are dislodged. After the cleaning period, the solvent containing wear debris was vacuum filtered through pre-weighed 47 mm diameter 0.45 μm pore size cellulose acetate membranes (now termed filter patches). After drying, the filter patches were weighed, the difference representing the mass of the engine wear debris collected. A cleaning time of 30 minutes was chosen for a recovery of debris between about 60 to 80 % (by mass) [4].

(2) Sample Dissolution: Filter patches were then dissolved in acid at high temperature through use of a microwave oven. A combination of three acids, HNO_3, HCl and H_2SO_4, was added to the samples in Teflon digestion vessels and placed in a microwave oven at 80% power for 5 minutes [4]. The filter patches were completely dissolved and some were analysed by AAS.

(3) Organic Conversion: The conversion method involves the use of a chelating agent. The chelate molecule readily attracts metal ions, making the ion soluble in oil. An excess of the chelating agents is used to ensure that the conversion of metal ions from aqueous to organic phase proceeds as desired. The chelating solution chosen was 1% 8-hydroxyquinoxine (oxine) in base oil [4].

A double extraction technique was developed and proceeded as follows. First, a buffer (2M ammonia and 3.17M ammonium bromide) was added and the reaction allowed to proceed to completion. Then 4.00M KOH and n-butylamine were added to bring the solution to a pH of 8.6. This solution and oxine in base oil were shaken and left long enough for the two phases to separate. The aqueous phase was collected for the second extraction and the oil was collected and set aside. To the aqueous solution, readjusted to a pH of 8.6, oxine in base oil was added, shaken and left to stand until the two phases separated. The second organic phase was added to the first and shaken so as to combine the two extraction products. The final aqueous phase was discarded. The organic phase containing most of the dissolved wear debris was then ready for analysis by RDE-AES.

The chemical preparation took approximately 4-5 hours for twelve samples (the capacity of the microwave oven). Calibration and standardization took approximately 4 hours. The actual analysis with the RDE-AES required less than 15 minutes for the twelve samples.

The metals which are extracted adequately include Fe, Ag, Al, Cu, Mg, Ni, Pb, Ti, Cd, Mn, V and Zn. (This order of elements is the order that the Baird FAS 2C and MOA analysis is read and is also the order from major to minor wear constituents). With the exception of magnesium, silver and titanium, all the metals are extracted with percent recoveries of >80%. The remaining metals suffer from various difficulties from a different detector response to standards and samples by the RDE-AES (Cr), relatively large reagent blanks (Na, Si, Sn) and poor extraction (Ba, B, Mo). Note that as long as these recoveries, although different, are consistent, trending is valid.

ENGINE FILTER DEBRIS RESULTS: Engine filters were received from Challenger, CF188 and USN F/A-18 aircraft, for a total of 121 filter debris patches. After the sample preparation described above, these were analysed by a Baird FAS-2C RDE-AES instrument. Wear rates are used to represent the wear debris data since oil filters are not always removed at consistent time intervals. The values from RDE-AES were adjusted in the following manner:

$$\text{ppm metal} = \frac{[(\text{measured ppm value}) \times (10.0 \text{ mL oil})]}{\left[\dfrac{\text{debris weight in g } [/2(\text{for half sample})]}{0.835 \text{ g/mL density of oil}}\right]}$$

This calculation takes into account the different amounts of debris from the various filters, the density of the oil, and that only half of the dissolved sample would have been used in the conversion to the organic sample. This latter calculation was included for those samples in which the other half of the dissolved sample was diluted and analysed by AAS in order to evaluate the organic conversion efficiency.

Wear rates (μg metal/h) were then calculated from the concentration results (ppm metal) to depict a time dependent picture of the condition of the aircraft engine as follows:

$$\text{ppm metal} \times \text{amount of prepared sample} = \mu\text{g metal}$$
$$\mu\text{g metal / interval between filter change} = \mu\text{g/h}$$

This calculation for wear rates gives an average value of mass of metal collected by the filter during the previous interval that the filter was in the system.

For the engines from the CF188 and USN F/A-18, the wear rate results for one of the twelve elements, iron, are shown in Figures 1 to 2 and reveal a definite pattern of grouped normal wear with few high values. To clearly show this, the average (dotted line) of all the wear rates as well as two standard deviations (2σ) from that mean (upper solid line) are plotted. The upper solid line marks a 95% confidence limit that all the results below this limit can be considered normal wear. Values above this line are considered abnormal wear. Rather than plot all of the elements which behaved in a similar manner, the grouping of the results are indicated in Table I, where the mean and two standard deviations are given for all twelve elements. Since consecutive samples were obtained for the Challenger aircraft, wear rate results for four metals (Fe, Al, Cu and Ni) are plotted consecutively for various engines in Figures 3 to 6.

Table I - Mean and Two Standard Deviations from Mean in μg/h for CF188, F/A-18 and Challenger Aircraft Engines

Elements	CF188		F/A-18		Challenger	
	Mean	2σ	Mean	2σ	Mean	2σ
Fe	0.4747	1.6813	6.11	13.27	4.1	12.7
Ag	0.0805	0.2543	2.51	13.28	2.2	6.6
Al	0.0259	0.0537	0.6	0.87	2.6	9.4
Cu	0.1128	0.4883	0.37	0.6	0.4	1.0
Mg	0.0032	0.0067	0.1	0.21	0.2	0.9
Ni	0.6270	2.4289	7.71	18.31	0.5	1.9
Pb	0.0451	0.0651	1.33	4.44	0.4	1.2
Ti	0.0068	0.0326	0.18	0.48	0.0	0.1
Cd	0.0119	0.0415	0.18	0.64	0.0	0.1
Mn	0.0055	0.0184	0.07	0.13	0.0	0.1
V	0.0056	0.085	0.07	0.12	0.1	0.2
Zn	0.0363	0.0893	0.48	0.96	0.3	0.7

CF188 Hornet F404 Engine Filter Debris Results: Twenty six CF188 engine filter debris samples were analysed for the 12 elements and, as an example, the wear rate for iron is shown in Figure 1, and the mean and 2σ are given in Table I for all the elements. The results gave trends similar to those found by Fisher [5] by INAA. The dominant wear constituents of the CF188 wear debris were found to be Fe, Ag, Cu, Ni and Zn. The elements Al, Mg, Ti, Pb, Cd, Mn and V were present in lower quantities.

Wear rates for engine serial #'s 376028 and 376269 are well outside the 95% confidence limit. From the records received from BFC Bagotville, these aircraft had known failures at the time the samples were taken. Engines 376028 suffered from a radial drive shaft failure (elements outside the 2σ limit are Fe, Ag, Cu, Ni and Mn) and engine 376269 was inspected because a metal chip was found in the metal screen plug. Since an analysis was not conducted at BFC Bagotville on the metal chip, it is uncertain that the elements found outside the limit (Ag, Al, Ni, Ti and Cd) were those found in the metal chip. The wear rates are outside the limit for two other engines 376268 (Pb) and 376022 (Cd and Zn). For these two aircraft, no major maintenance was found to have been conducted. Notice that the two engines with failures had five elements out of limit whereas engines 376268 and 376022 have only one or two elements out of limit. Possibly, only one element above the 95% confidence limit is an indication of a potential problem, but more than one element indicates a definite problem with the engine. This premise could be confirmed by a more extensive data base.

United States Navy F/A-18 Hornet F404 Engine Filter Debris Results: Thirty eight USN F/A-18 engine filter debris samples provided by the Joint Oil Analysis Program - Technical Support Center (JOAP-TSC) were analysed. The patch made at the JOAP laboratory (after cleaning for 5 minutes) [6] was added to the patch made at RMC (after cleaning for 30 minutes) and their masses added together. As an example, the wear rate results for iron are shown in Figure 2 and the mean and 2σ are given in Table I for all the elements. The results gave trends similar to those found by Fisher [5] by INAA. The dominant wear constituents of the USN F/A-18 wear debris were found to be Fe, Ag and Ni. The elements Al, Cu, Mg, Ti, Pb, Cd, Mn, V and Zn were present in lower quantities.

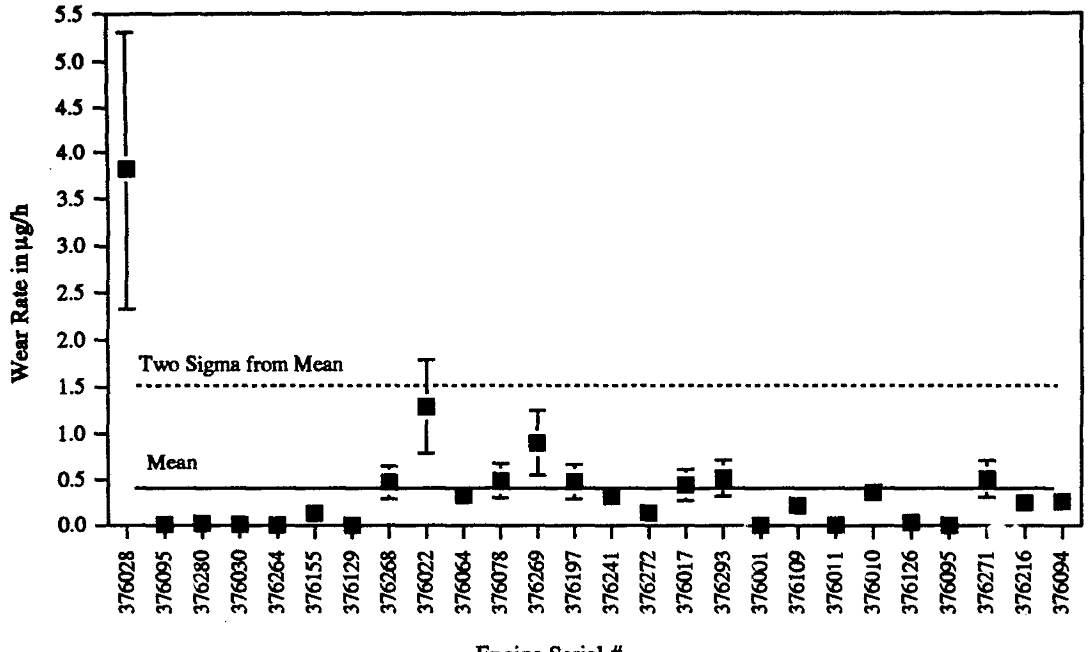

Figure 1 - Wear Rate of Iron from CF188 Engine Filters from April 94 to Dec 94

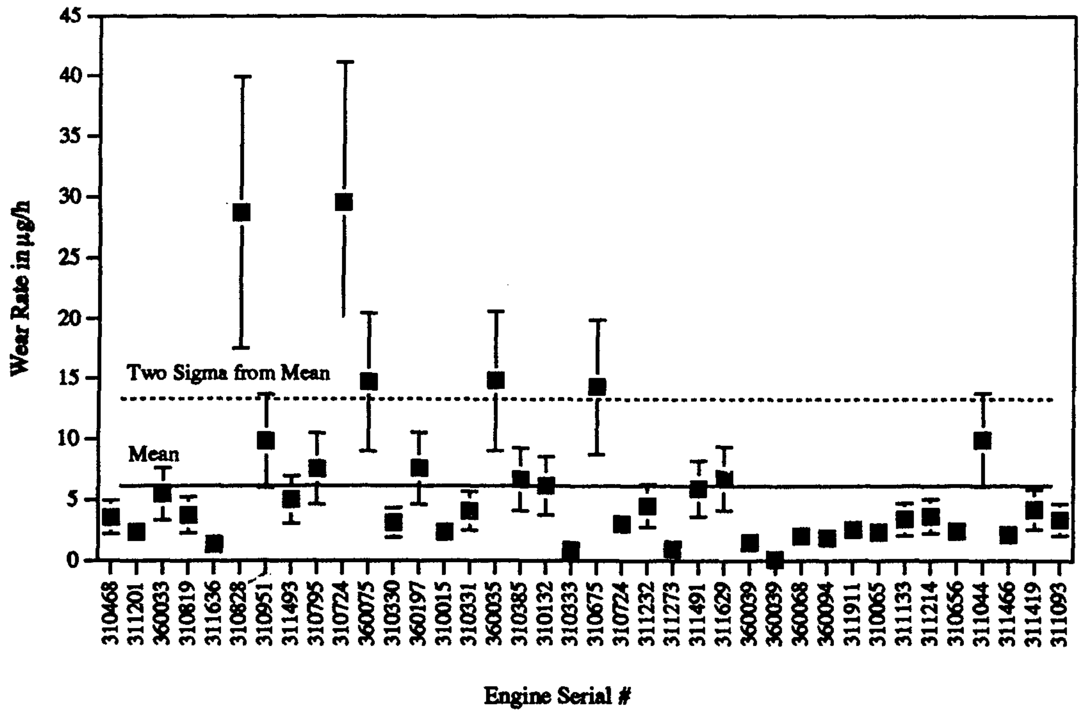

Figure 2 - Wear Rate of Iron from USN F/A-18 Engine Filters

Wear rates for engine 310828 are outside the 95% confidence limit for Fe, Al, Mg, Pb, Ti, Cd, Mn and Zn. Engine 310724 has wear rates outside the limit for Fe, Ni, Cd, Mn and V; engine 360075 for silver; engine 360035 for aluminum; and engine 311498 for lead. Confirmation of any difficulties with these engines is being requested through JOAP-TSC [6]. As no multiple engine samples were received, no engine trending can be shown.

Note that the wear rates for the USN F/A-18 aircraft are greater (as much as ten times) than those for the same engine type in the Canadian CF188. The US aircraft may be flown under more stressful performance conditions than the Canadian equivalent and the maintenance may be different.

CC144 Challenger ALF 502L-2C Engine Filter Debris Results: Fifty seven Challenger engine filter debris samples were analysed for 12 elements and the mean and 2σ are given in Table I. The dominant wear constituents of the Challenger wear debris were found to be Fe, Ag, Al, Cu, Mg and Ni. The elements Pb, Ti, Cd, Mn, V and Zn were present in lower quantities.

Since Challenger aircraft 604 and 605 have consecutive samples for a one to two year time period, trending can be demonstrated (Figures 3 to 6). The wear rate results for aircraft 604, engines 3061 and 3014 (replaced by 3038) are shown in Figures 3 and 4; the results for aircraft 605, engines 3189 and 3016 (replaced by 3163) are shown in Figures 5 and 6. All of the wear rate results show a similar pattern of grouped normal wear with few high values.

For aircraft 604, engine 3061 for 25 Sep 94 (Figure 3), the Fe and Al results are above their 2σ (39 μg/h and 33 μg/h, respectively) as are the other elements except Pb and Ti. In Figure 4, for engines 3014 and 3038, normal wear rates occur with all of the data points within the 95% confidence limit (see Table I for mean and 2σ values). However, engine 3014 has results for Ag, Cd, Mn and Zn above the 2σ limit. Engine 3014 was replaced by 3038 for time-expired maintenance.

In Figures 5 and 6, the wear rates for the left (3189) and right hand engines (3016, 3163) on aircraft 605 are plotted consecutively. In Figure 5, for aircraft 605, engine 3189 on 16 Jan 95 the wear rate for iron is above the 2σ limit at 27 μg/h (as are Al, Mg, Mn and V). The first three data points in Figure 6 are the wear rates of engine 3016 which was replaced by 3163. Apparently, engine 3016 was experiencing problems; however, the wear rates were normal for that engine. The last three points in Figure 6 were sampled at the same time (15 Oct 94, 20 Nov 94 and 16 Jan 95) as those in Figure 5. The wear rates for all elements for 16 Jan 95 (last data points) indicate an increase, although still within limits, except for Ag, Cd and V. Two explanations are possible, with the first being abnormal wear. However, aircraft 605 and 604 have been sent to a contractor for periodic maintenance so that any malfunction will be repaired. The second possibility and the more likely, since both engines are affected, is that the aircraft performed a flight profile that increased the loading on the engines which in turn increased the amount of wear. In this case, engine damage could only by concluded if that one engine did not have reduced wear rates at the next filter change.

DISCUSSION: Aircraft engines with fine filtration in their oil-lubricated systems cannot be monitored by the conventional AOA method. Most of the wear debris has been removed from the oil system and is in the oil filter. Previous work confirms that examining the wear debris from the oil filter does allow condition monitoring to be accomplished [5, 7]. Several analytical techniques are available for QFDA at various stages after the sample preparation. After the cleaning step (1), INAA could be employed, or after the dissolution step (2), AAS or ICP-AES could be used.

However, in order for QFDA to be employed in the field where the routine determination of the condition of the aircraft equipment in question is critical to safety and maintenance costs, the

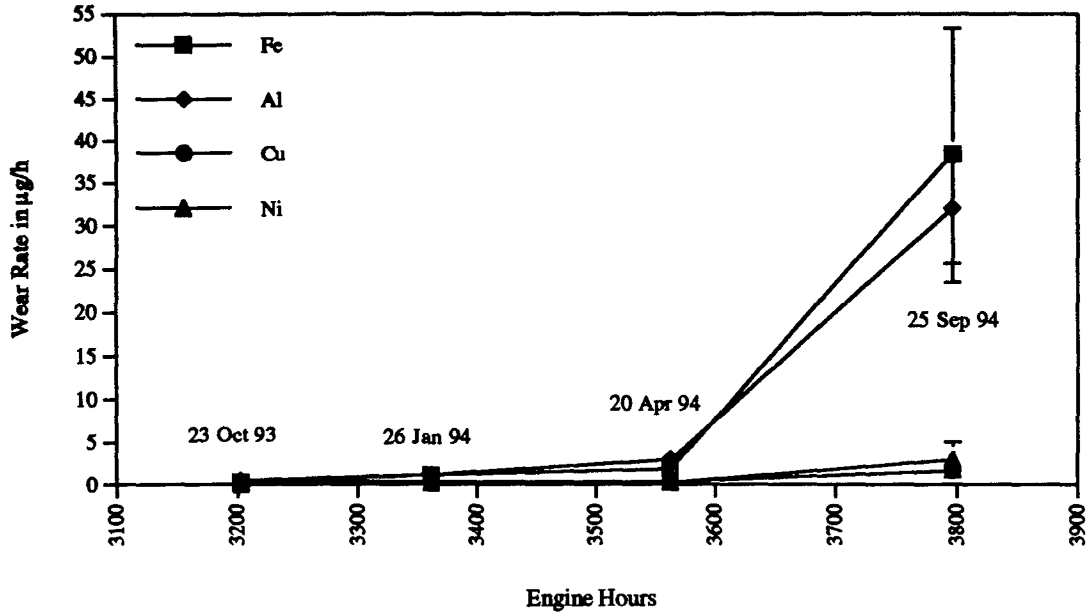

Figure 3 - Wear Rates from Challenger Engine Filters
Aircraft 604 Position #1 Engine 3061 from Oct 93 to Sep 94

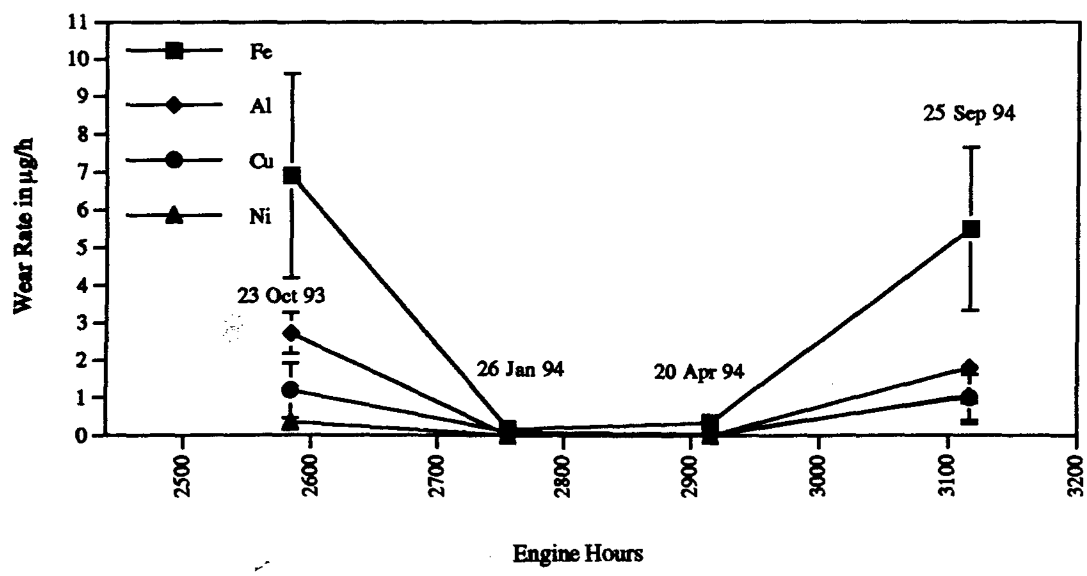

Figure 4 - Wear Rates from Challenger Engine Filters
Aircraft 604 Position #2 Engine 3014 & 3038 from Oct 93 to Sep 94

Note: Engine 3014 (first three data points) was replaced by Engine 3038 (last three data points)

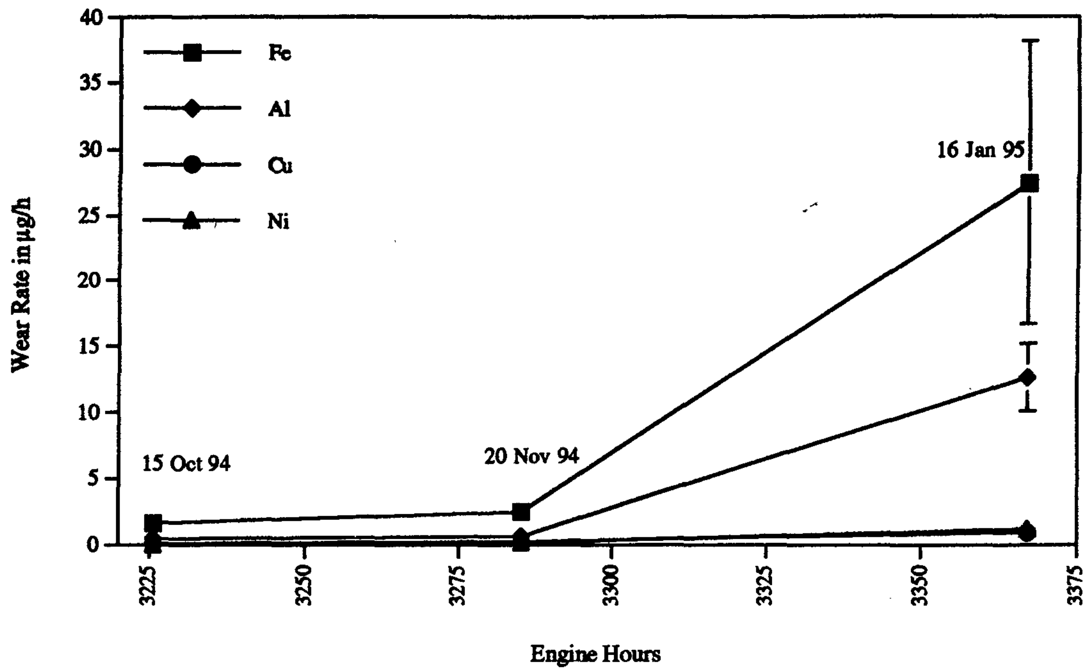

Figure 5 - Wear Rates from Challenger Engine Filters Aircraft 605 Position #1 Engine 3189 from Oct 94 to Jan 95

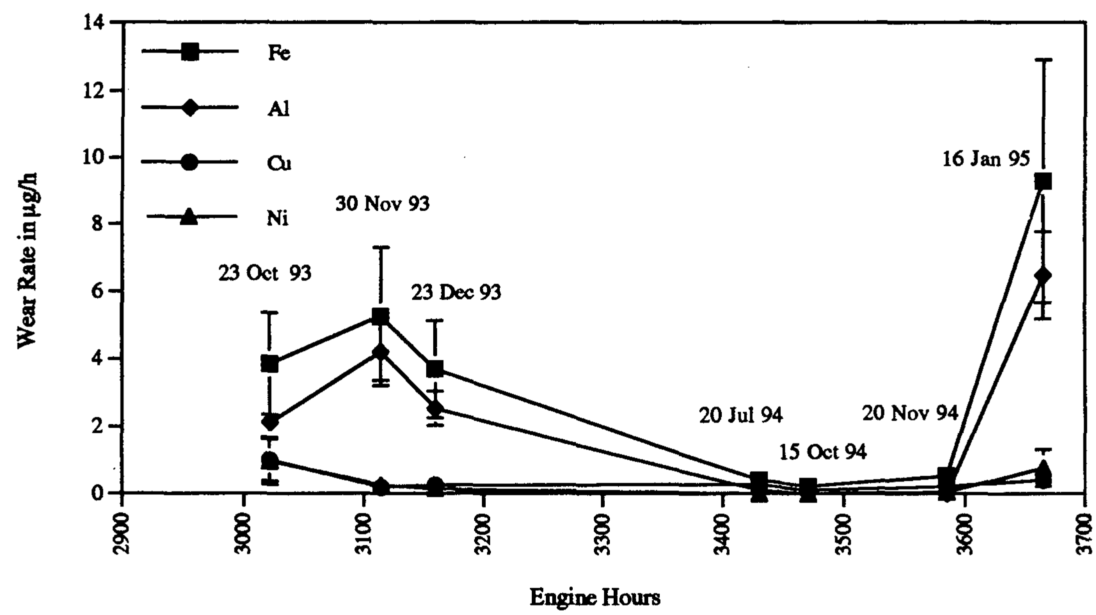

Figure 6 - Wear Rates from Challenger Engine Filters Aircraft 605 Position #2 Engine 3016 & 3163 from Oct 93 to Jan 95

Note: Engine 3016 (first three data points) was replaced by Engine 3163 (last four data points) technique has to be usable by aircraft technicians on RDE-AES instruments already acquired by the CF. Thus, the sample was prepared with three steps of cleaning, dissolution and conversion. The first two steps are relatively simple and fast in comparison to the third step which was carried out in order for the sample to be oil based. Even though each of these steps were kept as simple as possible, sample preparation requires four to five hours for batches of twelve.

The cleaning and dissolution steps are fairly straightforward and are not sensitive to small changes in procedure. The organic conversion step is the most time consuming. It is very sensitive to pH changes in the solution and very small changes in pH (± 0.5) can reduce the % recovery to zero. Of the three sample preparation steps, the conversion to an organic matrix contributed the most to the sample loss. This conversion loss was estimated by determining the % recovery for the elements of interest in known samples made from AAS standards [4].

However, in spite of these apparent difficulties, the wear rates of the actual filter debris samples showed that most samples were normal and a few were beyond the 95% confidence limit. This coincided with what was found previously with INAA [5]. Of the four CF188 samples with one or more elements out-of-limit, only the two with multiple elements were associated with actual failures (radial drive shaft failure and chip indication on metal screen plug). None of the normal samples were found to be failures. It appears that multiple out-of-limit results are required to indicate an engine failure.

Since only a small number of engine filter debris samples were received to date, the conclusion made above cannot be considered comprehensive, but it does point out that the technique is able to indicate failures. As more samples are received, a greater confidence in wear rate trending will be possible. As with any condition monitoring technique, the ability to determine whether the technique is pinpointing actual starts of failure is dependent upon the records and history kept on the corresponding components. The number of samples in this study are not sufficient to ensure that all points above the 2σ line are indicative of abnormal wear, but, with each additional sample and knowledge of its maintenance history, an acceptable limit for abnormal wear can be determined.

CONCLUSIONS: With the advent of fine filtration on new and old aircraft engines and related components in the CF, the ability to monitor effectively the condition of those components by current practices, such as AOA, has been decreased. The potential for QFDA to monitor wear debris from the oil-lubricated components has been shown. Filter debris samples from the Challenger, the CF188 Hornet and the USN F/A-18 aircraft engines were analysed to indicate the levels of normal wear rates for twelve elements.

The calculated wear rate results for the Hornet and Challenger aircraft revealed that two distinct levels of wear can be indicated as normal and abnormal wear. By using a normal distribution, the abnormal wear rate level was set at the 95% confidence limit. Usually there was a wide gap observed between the normal and abnormal wear rate regions so that the difficulties with the % recoveries used in the conversion step will not affect the determination of abnormal wear rates. The wear rates for the elements showed moderate scatter about a standard mean. The 95% confidence limit was successful in determining abnormal wear in two CF188 engines that experienced failure. The other samples were generally well below this limit. Overall, the F/A-18 aircraft engines experiênced higher wear rates than the same type of engine on the CF188 Hornet. With more samples and a different mean, these might be considered normal wear. This research demonstrated that trending the wear rates of wear elements by the proposed technique can provide a means of monitoring the condition of aircraft engines.

RECOMMENDATIONS: QFDA investigations should be continued for the ALF 502L-2C and F404 engines in order to continue building a data base. This technique could be expanded to other candidate engines and related components. A project has been started to involve unit personnel in the evaluation and implementation of this technique in the AOA laboratories. The sample preparation procedure efficiency, especially the % recovery for the conversion step, should be determined by using actual samples and by comparing other techniques (i.e., INAA and AAS). Other analytical techniques such as ICP-AES, which is an appropriate method of analysing trace metal content in acid solutions, could be studied.

References

1. Morin, J., "Canadian Air Force Condition Monitoring Program", Joint Oil Analysis Program - International Condition Monitoring Conference, Department of Defense: Florida, 1992.
2. Flanagan, I.M. et al, Wear-debris detection and analysis techniques for lubricant-based condition monitoring, Journal of Physics E Scientific Instruments, Vol 21, 1011-1016, 1988.
3. Waggoner, C.A., Application of Diagnostic Wear Debris Analysis to CF188 Aircraft Engines, DREP: Esquimalt, 1988.
4. Swanson, S.A., Quantitative Filter Debris Analysis: Sample Preparation for Analysis by Rotating Disk Electrode Atomic Emission Spectrophotometry, M. Eng. Thesis, Royal Military College, Kingston, 1995.
5. Fisher, G.F., Quantitative Filter Debris Analysis (QFDA) as a Means of Monitoring Wear in Oil-Lubricated Systems, M.Eng. Thesis, Royal Military College, Kingston, 1991.
6. Humphries, G., personal communication, Nov, 1994.
7. Harper, W.A., The Determination of Wear Elements in Engine Lubricating oils and Filters by Neutron Activation Analysis, M.Eng. Thesis, Queen's University, Kingston, 1988.

Acknowledgments

This research was supported financially by the Head/Air Vehicle Research Section 3, the Directorate of Technical Airworthiness 3 of the National Defence Headquarters, and the Principal, Royal Military College of Canada - Collège militarie royal du Canada. The participation of BFC Bagotville, CFB Cold Lake and CFB Shearwater in sending oil filters and records is also gratefully acknowledged.